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DESIGN OF NON DESTRUCTIVE TESTING ON COMPOSITE MATERIAL USING PARALLEL PLATE ELECTRICAL CAPACITANCE TOMOGRAPHY: A CONCEPTUAL FRAMEWORK

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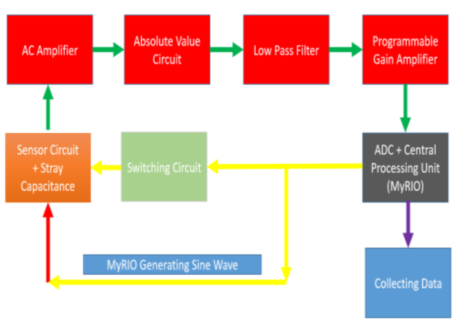
Graphical abstract



Abstract

In this paper, a conceptual framework for a non destructive testing to check defect on composite material using parallel plate electrical capacitance tomography is being proposed. At the early stage, the possibility of using this method is being simulated using Comsol Multiphysic software. The simulation process has shown promising results to make this concept works. When a dielectric material is placed between the parallel plates, the permittivity distribution can be observed. As the number of electrodes of the sensor are increased from 2 to 8 electrodes, the capacitance value increase from $2.0131e^{-11}$-$2.3532e^{-14}$i F to $5.2474e^{-11}$-$3.0756e^{-13}$i F. Furthermore, there are significant results when the size and the permittivity of the object are varies.

Keywords: Dielectric, composites, electrical capacitance tomography, miniature parallel plates, LabVIEW, MyRIO

1.0 INTRODUCTION

A composite material or also known as composition material is a material produced using two or more different materials with fundamentally distinctive physical or chemical properties that, when joined, produce a material with unique qualities compare to the individual parts. The individual segments can be distinguished inside of the completed structure. The new material might be favored for some reasons including materials which have more strength, lighter, or cheaper compared to conventional materials [1], [2]. Due to these reasons, they are very popular for use in aircraft and wind turbine blades for example the main landing gear brace for the Boeing 787-8 Dreamliner, LiftFan for the Rolls-Royce F-35 Lightning II and fan blades and casings in the CFM International Leading Edge Aviation Propulsion (LEAP) engine [3]. A great deal of previous research into composites has focused on the properties of composites material [4]–[7], composites structures [8], [9] and composites defect [10]. Besides, there are a considerable amount of literature has been published on nondestructive testing (NDT) to check and test specific problems in producing composite materials.

Defects in composite materials may be contributed during processing and fabrication and also during service under loading and environmental variations. Defects which are produced during processing and fabrication include contaminants, porosity, inclusions, delamination, and non uniform fiber and matrix distributions. On the other hand, other defects such as matrix cracking, delamination, fiber breakage, matrix ageing and degradation are normally introduced during service [11]. It is very crucial to ensure the safety operation of composite materials since it is one of the main components in manufacturing aircraft, therefore, non destructive testing (NDT) or non destructive evaluation (NDE) are used during both manufacturing and operation of the materials [12].

A variety of NDT methods have been used for composites, however each of methods or techniques are suitable for specific applications or problems. The sensitivity and effectiveness of such NDT methods are discussed in various articles in connection with three applications namely thick composites, metal-matrix composites, and fatigue damage[13]. Different techniques and methods exist in the literature regarding ultrasonic testing on composites [14], [15] and one of the latest ultrasonic technique is by using pulse laser coupled with an optical fiber to generate ultrasonic signals which has been proposed by Guangkai *et al.* [9]. Another technique which is normally used to examine composites is acoustic emission (AE). This technique is capable for identifying different sorts of defects mechanism in composite materials [16]. A considerable amount of literature has been published on AE [17]. Besides, quite a number of publications has mentioned about the usage of x radiography techniques [18]. More recent attention has focused on the application of thermography technique to examine defect in composites. Ruizhen *et al*. has focused on developing new technique using selectively heating thermography through electromagnetic induction [19]. A few recent publications have discussed about thermography techniques extensively [20] which offer a wide range of techniques of choice for NDT on composites.

To date, surprisingly, the application of electrical capacitance tomography (ECT) on composites, has still not yet been comprehensively investigated. Very few published studies have adequately tested the effectiveness of ECT on dielectric materials [21], [22]. To the author's knowledge to date, no investigation has been made on the NDT to check problems on composite materials using ECT [23]. Therefore, there are a lot of opportunities and studies can be done regarding the application of ECT on composite materials. The objective of the present work paper is to investigate the effectiveness of the parallel plate electrical capacitance tomography to check the defect on composite materials. The contribution of this study is obvious as the resulting outcomes can be capitalized as the starting point to explore the possibility of using ECT as one of the NDT techniques on composites.

2.0 METHODOLOGY

The basic idea of tomography is to install a number of sensors around the measured subject. The information of the measured subject can be obtained based on the distributions and nature of the components within the sensing zone. For ECT, the main component which will become the subject of measurement is the variations in the dielectric properties of the material between the parallel plates. Different dielectric properties between conductors will create different capacitor values.

Using finite element method (FEM), the relationship between capacitance and permittivity distribution can be expressed as

$$C = \frac{Q}{V} = -\frac{1}{V}\iint \varepsilon(x,y)\nabla\emptyset(x,y)d\Gamma \qquad (1)$$

where V is the potential difference between two electrodes, $\varepsilon\,(x,y)$ is the permittivity distribution in the sensing field, $\emptyset(x,y)$ is the potential distribution and Γ is the electrode surface.

According to the Maxwell's equation, the internal electric charge of the electrostatic field is zero. Therefore, the ECT sensor model can be described as

$$\nabla\big(\varepsilon(x,y)\nabla\emptyset(x,y)\big) = 0 \qquad (2)$$

The electrical potential distribution is then derived as

$$E(x,y) = -\nabla\emptyset(x,y) \qquad (3)$$

For simulation, 2D FEM models of two-plates ECT sensors were generated in COMSOL. There are several stages of the ECT system simulation process and the development process is listed as follows:

(i) The designing of forward modelling process for ECT sensor model by implementing the COMSOL Multi-physics software.
(ii) Forward modeling simulative study in analyzing the capacitance non-linear changes which caused by the higher dielectric material increase of diameter using;
   (a) Single excitation potential, single-electrode excitation scheme
   (b) Two different excitation potentials, single-electrode excitation scheme
(iii) Simulating the distribution of sensitivity within the sensing region.
(iv) The capacitance measurements, sensitivity and permittivity distribution normalization process.
(v) The image reconstruction permittivity distribution simulative study which is done for

single excitation potential and single-electrode excitation.

There are a few reasons which contribute to the development of forward modelling using COMSOL Multi-physics. One of the reason is to find the characteristic of the capacitance sensor. Another reason is to acquire the capacitance between terminals amid the operation of an electric field with Finite Element Method and at the same time to get the permittivity distribution between the parallel plates of the sensor. Besides, the capacitance changes between contrasting electrodes and the dielectric material permittivity can be initiated.

In the simulation, the sensor model is built and simulated to calculate the capacitances between all possible electrode pairs. The sensor geometry will have to follow the actual size of the hardware. The configurations of sensor are:

- Length of shielding layers and wall: 21mm
- Electrode Length: 9mm
- Gap between adjacent electrodes: 1mm
- Material of shielding layers and electrode: copper
- Material of wall: FR4 ($\varepsilon_r = 4.8$)

Previous research [24]–[26] shows that most of the ECT system is applicable in flow visualization (image reconstruction). The concentration profile obtained from capacitance measurements describes the liquid and gas mixture in pipelines while system development is designed to be attached on a vessel. The electrode plated, which previously act as sensors, are assembled and fixed on the pipeline, obscuring the production for any new process installation in the future. Most of the ECT systems are in circular shape in order to encircle the circular type of pipelines. However, the new approach of the parallel plate sensor in this work allows the flexibility of the sensor to be assembled and moved by following the shape of the composites specimens. The system is designed to accommodate different shape of composites specimens and a number of electrode sensors will be determined based on the simulation and actual study.

In this study, electrodes will be fabricated on a FR4 material. The number and the position of electrodes will be studied based on actual experiments using the experiment set up. The thickness of the specimen can also influence the measured value of the standing capacitance. There are a few factors which can influence the value of the standing capacitor. These factors include the thickness of the specimen, the permittivity of the specimen, distance between parallel plate and the angle of elevation of the parallel plate. The effect of these factors to the reading will be studied thoroughly by undergoing different experiments. The placement of electrodes on the specimen will be done carefully to ensure that the electric filed produced during excitation is uniformly distributed among the receiving electrodes.

The measurement circuit can be divided into a few parts like the capacitance measurement circuit, filter circuit, amplifying circuit as well as the AC to DC converter circuit. A part from those, a sine wave generator is also needed to function as the excitation source for the sensor electrodes. The data will be yielded by the electronic devices which will later be sent to the data acquisition system for analog to digital conversion purpose. Next on the step, the digital data will be sent to a computer for analysis and image reconstruction. A control unit is set to synchronize all operations and it will move the data to the control PC. The measurements reading as received by a control PC will then keep the picked up data, rebuild images from the integral measurements and lastly gives feedback about the defect on the specimens.

A main controller unit is used to synchronize all operations on collecting measurement data and sending data to a PC for image reconstruction. It is used to synchronize all transmitted and received operations on sensor. The main controller unit that will be used is NI MyRio. This high performance and powerful controller is developed by National Instruments is selected in the present study. This controller can act as a standalone Data Acquisition System (DAS) capable of working independently. For this project, the controller will be configured as the main controller to synchronize the whole system, besides, it will act as the function generator and also as the analog digital convertor.

Overall, the hardware is working standalone, which means the main control unit will oversee the whole process after receiving instructions from a host computer. The main control unit continuously controls the measuring operation, collecting data from electrode modules and sending data the host computer for image reconstruction.

3.0 RESULTS AND DISCUSSION

Zhen Ren *et al.* [27], [28] has done comprehensive study on miniature parallel plate study. She has studied the model of sensor, the effective sensing area, the distance between two sensor plates, angle between two plates and number of electrodes. Her study has shown promising results. She found out that, a too small or too large sensing area results in too high sensitivity near the edge and relatively low sensitivity in the central region, producing low contrast images and distortion. Besides, she has concluded that, a smaller distance between the two plates will produce a higher sensitivity at the central region. Author added that, two plate ECT sensor is very useful to sense specimen with special geometry which is actually related to the shape of any composite material.

Factors thought to be influencing the reading of capacitance sensor have been explored in several studies. Xiaohui Hu *et al.* [29] has provided a comprehensive study about capacitance sensors which is focusing on the sensing mechanism, design issues, performance test and the application of the sensor. He has concluded that the capacitance value from the sensor are related to the properties and the position of object which is being tested.

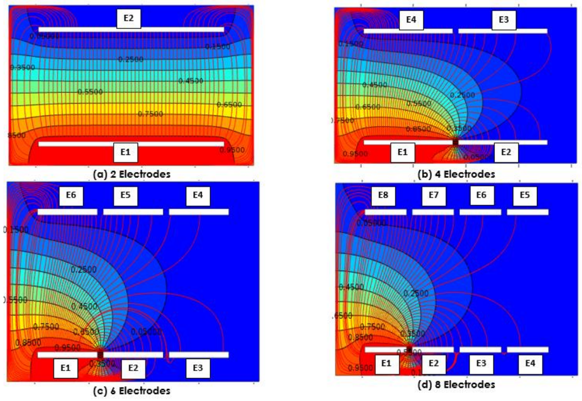


Figure 1 Contours of electric potential and electric field lines when electrode 1 is excited

Performance of parallel ECT has been studied using Comsol Multiphysics software. When the size of the specimen is increased, electric field lines relatively follow the shape of the specimen. Besides, the permittivity of the specimen can also influence the pattern of the electric filed lines which flow between parallel plates [30]. Figure 1 shows the sensors with 2, 4, 6 and 8 electrodes whereby voltage is excited from electrode 1 (E1) to the rest of the electrodes which are grounded. In the simulation, test object (composite material) is put between two parallel plates and the reading of capacitance will be taken. This can be depicted from Figure 2, where phantom is the test subject which represent the composite material.

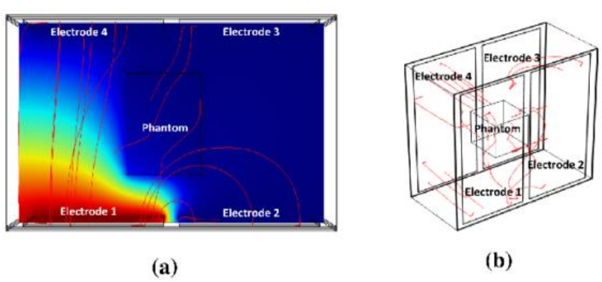


Figure 2 Phantom (composite material) from (a) 2D and (b) 3D simulation respectively

In the simulation, there were two types of composites which have been used as test subject namely carbon fiber/epoxy and FR4. In the beginning, the test subject without defect was tested with different design of sensors and the reading were taken. Next, test object with void (air) was put between the sensors to measure the capacitance readings. Table 1 shows the capacitance readings of these simulations and difference of results between material under test with void and material under test without void can be clearly seen as plotted in graph Figure 3. We can see that the capacitance values of test object with and without defect are different. Therefore, this is an evident to support the idea that defects on composite materials can be detected.

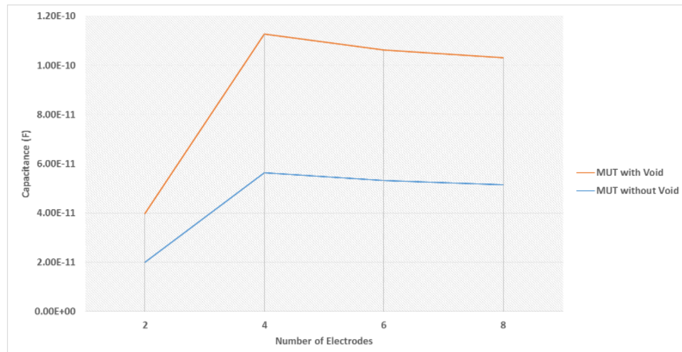


Figure 3 Capacitance readings of sensor on composite materials with void and without void

From the simulation, the distribution of the electrical field and electric potential can be observed varies depends on the properties of the material under test. Figure 4 shows the pattern of electrical field and electrical potential change as it coincide with a round shape which is depicted as void which is introduced in the material under test.

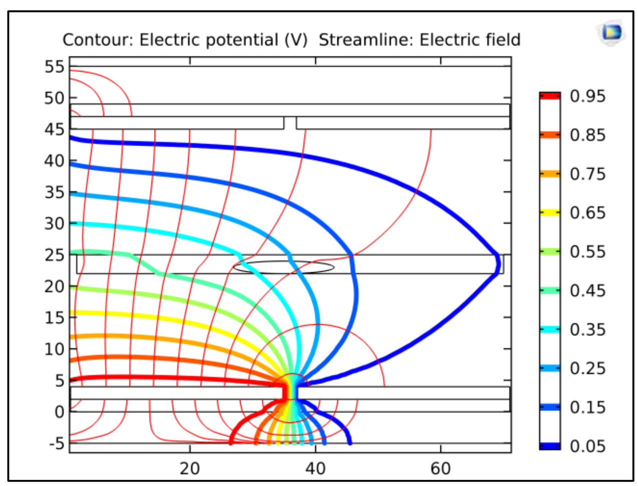


Figure 4 The distribution of electrical potential and electrical field lines between two parallel plate sensors

Table 1 Error! No text of specified style in document.The reading of capacitance values from the sensor model with composites without and with defect

Number of Electrodes	Types of Composites	Capacitance value (F) without defect	Capacitance value (F) with defect
2	Carbon fiber/epoxy	2.0131e^{-11}-2.3532e^{-14}i	2.0043e^{-11}-3.70939e^{-14}i
	FR4	1.99e^{-11}	1.98e^{-11}
4	Carbon fiber/epoxy	5.7812e^{-11}-4.6951e^{-13}i	5.7412e^{-11}-4.4514e^{-13}i
	FR4	5.64e^{-11}	5.63e^{-11}
6	Carbon fiber/epoxy	5.4349e^{-11}-3.9319e^{-13}i	5.4074e^{-11}-3.6890e^{-13}i
	FR4	5.32e^{-11}	5.31e^{-11}
8	Carbon fiber/epoxy	5.2474e^{-11}-3.0756e^{-13}i	5.2321e^{-11}-2.8779e^{-13}i
	FR4	5.15e^{-11}	5.15e^{-11}

4.0 CONCLUSION

For the conclusion, these results further support the idea of establishing a parallel plate ECT system to check the defect on composite material. Furthermore, this study has thrown up many questions in need of further investigation. Since this work is to propose a conceptual framework of applying ECT in NDT to check composites, based on the obtained results, further work needs to be done to establish whether parallel ECT can distinguish the type of defects which appear on composite material such as delamination or crack.

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